

Decay of Hypernuclei

A. Parreño^{* a}, C. Bennhold^b and A. Ramos^c

^aInstitute for Nuclear Theory, University of Washington, Box 351550
Seattle, WA 98195-1550

^bCenter of Nuclear Studies, Department of Physics,
The George Washington University, Washington, D. C. 20052

^cDepartament d'Estructura i Constituents de la Matèria, Facultat de Física,
Diagonal 647, E-08028 Barcelona

We present a nonrelativistic transition potential for the weak strangeness-changing reaction $\Lambda N \rightarrow NN$. The potential is based on a one meson exchange model (OME), where, in addition to the long-ranged pion, the exchange of the pseudoscalar K, η , as well as the vector ρ, ω, K^* mesons is considered. Results obtained for different hypernuclear decay observables are compared to the available experimental data.

1. Introduction

As is well known, the mesonic decay ($\Lambda \rightarrow \pi N$) of a Λ particle in the nuclear medium is highly suppressed due to the Pauli blocking effect acting on the outgoing nucleon. In contrast, the nonmesonic (NM) decay mode ($\Lambda N \rightarrow NN$), where the mass difference between the initial hyperon and nucleon is converted into kinetic energy for the outgoing nucleons, is the dominant decay mode for medium to heavy hypernuclei.

During the last thirty years, many theoretical works have described the NM decay of hypernuclei by mainly using two different approaches: a description in terms of quark degrees of freedom or/and the use of a OME model. A recent review of the present status of the theoretical and experimental situation can be found in Ref. [1].

The OME approach is the one that will be presented in this contribution. In order to draw conclusions regarding the weak dynamics, nuclear structure details have to be treated with as few approximations and ambiguities as possible. Working in a shell-model framework, spectroscopic factors are employed to describe the initial hypernuclear and final nuclear structure. To reduce the uncertainties regarding initial and final short-range correlations we use realistic ΛN and NN strong interactions based on the Nijmegen baryon-baryon potential. More details about this calculation can be found in Ref. [2].

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2. The Meson Exchange Potential

In a OME model, the transition $\Lambda N \rightarrow NN$ is assumed to proceed via the exchange of virtual mesons belonging to the ground-state pseudoscalar and vector meson octets. The nonrelativistic reduction of the free space Feynman amplitude involving a weak and a strong baryon-baryon-meson (BBM) vertex, gives the nonrelativistic potential in momentum space [2]. The $\Delta I = 1/2$ rule, which is experimentally known to hold in the free Λ decay, has been assumed when computing the NM amplitudes. How to account for possible violations of this rule and their consequences is discussed below. For pseudoscalar mesons, the transtion potential reads:

$$V_{ps}(\mathbf{q}) = -G_F m_\pi^2 \frac{g}{2M} \left(\hat{A} + \frac{\hat{B}}{2\bar{M}} \boldsymbol{\sigma}_1 \mathbf{q} \right) \frac{\boldsymbol{\sigma}_2 \mathbf{q}}{\mathbf{q}^2 + \mu^2}, \quad (1)$$

where $G_F m_\pi^2 = 2.21 \times 10^{-7}$ is the Fermi weak coupling constant, \mathbf{q} is the momentum carried by the meson, $g = g_{\text{BBM}}$ the strong coupling constant for the BBM vertex, μ the meson mass, M the nucleon mass and \bar{M} the average between the nucleon and Λ masses. The operators \hat{A} and \hat{B} contain the weak parity violating (PV) and parity conserving (PC) coupling constants respectively, as well as the isospin dependence of the potential. For vector mesons the potential has the form:

$$V_v(\mathbf{q}) = G_F m_\pi^2 \left(F_1 \hat{\alpha} - \frac{(\hat{\alpha} + \hat{\beta})(F_1 + F_2)}{4M\bar{M}} (\boldsymbol{\sigma}_1 \times \mathbf{q})(\boldsymbol{\sigma}_2 \times \mathbf{q}) - i \frac{\hat{\varepsilon}(F_1 + F_2)}{2M} (\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \mathbf{q} \right) \frac{1}{\mathbf{q}^2 + \mu^2} \quad (2)$$

with $F_1 = g_{\text{BBM}}^V$ and $F_2 = g_{\text{BBM}}^T$ the vector and tensor strong couplings. The (PC) $\hat{\alpha}$, $\hat{\beta}$ and (PV) $\hat{\varepsilon}$ operators contain the isospin structure together with the corresponding weak couplings. In the case of isovector mesons (π, ρ) the isospin factor is $\boldsymbol{\tau}_1 \boldsymbol{\tau}_2$, and for isoscalar mesons (η, ω) this factor is just $\hat{1}$ for all spin structure pieces of the potential. In the case of isodoublet mesons (K, K^*) there are contributions proportional to $\hat{1}$ and to $\boldsymbol{\tau}_1 \boldsymbol{\tau}_2$ that depend on the coupling constants and, therefore, on the spin structure piece of the potential.

In order to account for the finite size and structure of baryons and mesons, a monopole form factor $F(\mathbf{q}^2) = (\Lambda^2 - \mu^2)/(\Lambda^2 + \mathbf{q}^2)$ is considered in both the strong and weak vertices, where the value of the cut-off, Λ , different for each meson, is taken from the Jülich YN interaction[3]. To incorporate the effects of the NN interaction, we solve a T-matrix scattering equation in momentum space, which describes the relative motion of two nucleons moving under the influence of the strong interaction. For the strong NN interaction we use the updated version of the Nijmegen NN potential[4]. For the bound ΛN state, we replace the uncorrelated shell-model ΛN wave function (for which we take harmonic oscillator solutions) by a correlated ΛN wave function that contains the effect of the strong ΛN interaction. This wave function is obtained by taking, as a guide, microscopic finite-nucleus G -matrix calculations[5] using the soft-core and hard-core Nijmegen models[6]. It has been shown [7] that multiplying the uncorrelated ΛN wave function with the spin-independent correlation function

$$f(r) = \left(1 - e^{-r^2/a^2} \right)^n + b r^2 e^{-r^2/c^2}, \quad (3)$$

with $a = 0.5$, $b = 0.25$, $c = 1.28$, $n = 2$, yields decay rates which lie in between those using the hard and soft Nijmegen ΛN potential models. Since the deviations were at most 10% the above parametrization can be used as a good approximation to the full correlation function.

The strong BBM couplings are taken from either the Nijmegen[6] or the Jülich [3] potentials. In the weak sector, only the couplings corresponding to decays involving pions are experimentally known. The weak couplings involving mesons heavier than the pion are obtained following Refs. [8,9]. The PV amplitudes for the nonleptonic decays $B \rightarrow B' + M$ involving pseudoscalar mesons are derived using the soft-meson reduction theorem and SU(3) symmetry, which allows us to relate the physical amplitudes of the nonleptonic hyperon decays into a pion plus a nucleon or a hyperon, $B \rightarrow B' + \pi$, with the unphysical amplitudes of the other members of the meson octet (K, η). On the other hand, SU(6)_w permits relating the amplitudes involving pseudoscalar mesons with those of the vector mesons. The pole model, where the pole terms due to the $(\frac{1}{2})^+$ ground state (singular in the SU(3) soft meson limit) are assumed to be the dominant contribution, is used for obtaining the PC coupling constants.

3. Results

In Table 1 we explore the effect of including all the mesons on the weak decay observables for the ^{12}C hypernucleus. These observables include: the NM decay rate in units of the free Λ decay rate, $\Gamma_\Lambda = 3.8 \times 10^9 \text{s}^{-1}$ (second column), the fraction between the neutron ($\Lambda n \rightarrow nn$) and the proton ($\Lambda p \rightarrow np$) induced decays (third column) and the intrinsic Λ asymmetry parameter, a_Λ , characteristic of the elementary $\bar{\Lambda}N \rightarrow NN$ reaction taking place in the nuclear medium (last column). This last parameter is related to the observed angular asymmetry in the distributions of protons coming from the decay of polarized hypernuclei. The numbers between parenthesis are obtained when the Jülich constants are used in the strong vertex instead of the Nijmegen ones. Note that, through the pole model, this choice of strong coupling constants would also affect the couplings in the PC weak vertices. However, we keep them fixed to the values obtained using the Nijmegen model and modify only the strong vertex. This allows us to assess the effect of using different sets of strong couplings derived from YN potentials that fit the hyperon-nucleon scattering data equally well.

Even if not shown here, the pion-exchange (OPE) contribution dominates the rate not only in magnitude but in range, a consequence of the pion being the lightest meson. This rate is especially sensitive to the inclusion of the strange mesons, while including the ρ -meson has almost no effect. Note that the contribution of each isospin-like pair $[(\pi, \rho), (K, K^*), (\eta, \omega)]$ interferes destructively, so, the reduction caused by the K meson is mostly compensated for by adding the K^* . A similar situation is observed between the η and ω mesons, consequently their combined effect on the rate is negligible. The final result for the rate is 15% smaller or greater than the pion-only one, depending on the choice of couplings in the strong sector. This sensitivity is unfortunate since it will certainly complicate the task of extracting weak couplings from this reaction. Improved YN potentials which narrow the range of the strong coupling constants are required to reduce this uncertainty. Table 1 also shows the results obtained when the NNK weak

coupling constants derived with one-loop corrections to the leading order in χ PT[10] are used (last row). Due to the smaller value of the coupling constants the effect of the K meson is reduced and thus the total rate is increased by about 10%.

It has been known for a long time that the large tensor transition ($^3S_1 \rightarrow ^3D_1$) in the OPE mechanism, where only $T = 0$ np pairs can occur, is the reason for the small value of Γ_n/Γ_p given by pion exchange alone[11]. For many years, it was believed that the inclusion of additional mesons would dramatically increase this observable. But here, we find the opposite to be true. This ratio is, as expected, quite sensitive to the isospin structure of the exchanged mesons, and it is again the inclusion of the two strange mesons that dramatically modifies this partial ratio. Including the K -exchange which interferes destructively with the pion amplitude in the neutron-induced channel leads to a reduction of the ratio by more than a factor of three. The K^* , on the other hand, adds constructively. Using the Nijmegen strong couplings constants leads to a final ratio that is 34% smaller than the pion-only ratio, while using the Jülich couplings leaves this ratio unchanged, due mostly to the larger K^* and ω couplings. Employing the weak NNK couplings calculated with χ PT increases the Γ_n/Γ_p ratio by 17% with Nijmegen couplings while the ratio remains unchanged for the Jülich model.

The intrinsic asymmetry parameter, a_Λ , is also found to be very sensitive to the different mesons included in the model. This is the only observable which is changed dramatically by the inclusion of the ρ , reducing the pion-only value by more than a factor of two. Adding the other mesons increases a_Λ , leading to a result about 30% or 50% larger than for π -exchange alone, again depending on the type of strong couplings used.

Our final results for various hypernuclei are compared with experimental data in Table 2. We find overall agreement between our results for the nonmesonic rate and the experimental values, especially when the χ PT weak couplings for the K meson are used. The situation for the Γ_n/Γ_p ratio is different, and the theoretical values greatly underestimate the newer central experimental ones, although the large experimental error bars do not permit any definite conclusions at this time. On the other hand, the proton-induced rate which has errors of the same magnitude as the total rate is overpredicted by our calculations by up to a factor of two. Even though Γ_n and Γ_p appear in disagreement with the data, their sum conspires to give a total rate which reproduces the measurements.

Motivated by the hope that $\Delta I = 1/2$ violations would affect the Γ_n/Γ_p ratio, we studied the effect of allowing $\Delta I = 3/2$ transitions in the vector meson exchange potential[12]. The new weak couplings were derived in the factorization approximation and, in order to take into account the limitations imposed by this derivation, we allowed them to vary by up to a factor of ± 3 . While the total decay rate changed by at most 6%, the Γ_n/Γ_p ratio could be enhanced by a factor of 2, for different combinations of the multiplying factors. These modifications were almost due to changes in Γ_n ; Γ_p was barely affected. Even though the estimates based on the factorization approximation are rather crude, the variation on the results for the Γ_n/Γ_p ratio and for the asymmetry parameter (which can be altered by a factor of 7) clearly indicates that one cannot assume the validity of the $\Delta I = 1/2$ rule. Experiments measuring partial decay rates of light hypernuclei are desirable in order to clarify the validity of such rule.

Regarding the asymmetry parameter, comparison with experiment can only be made at the level of the measured proton asymmetry, which is determined as a product of a_Λ ,

characteristic of the weak decay process, and the polarization of the Λ inside the hypernucleus, p_Λ , characteristic of the strong formation process and which must be determined theoretically. In order to avoid the need for theoretical input and access A_p directly, a new experiment at KEK has measured the decay of polarized ${}^5_\Lambda\text{He}$ extracting the pion asymmetry from the mesonic channel, \mathcal{A}_{π^-} [13]. The asymmetry parameter a_{π^-} of the pionic channel has been estimated to be very similar to that of the free Λ decay [14], and, therefore, the hypernuclear polarization is obtained from the relation $P_y = \mathcal{A}_{\pi^-}/a_{\pi^-}$. This value, together with the measurement of the proton asymmetry from the nonmesonic decay has allowed to get the value of a_Λ for ${}^5_\Lambda\text{He}$, which has been quoted as 0.22 ± 0.20 [15], in disagreement with the present theoretical predictions.

4. Summary and Outlook

Total decay rates evaluated with the full weak OME potential fall within 15% of the value obtained with pion exchange only and reproduce the experimental data. This is partly due to the destructive interference between the contributions of the heavier mesons whose individual influence on the decay rate can be substantial. The importance of kaon exchange makes it possible to see the effects of modifying the weak NNK couplings by one-loop corrections to the leading order in χ PT. Including these loop graphs leads to a reduction of the NNK couplings from their tree-level value up to 50%, which in turn modifies the decay rate by up to 20%. Future experiments should be able to verify this effect. We found the influence of strange mesons to be even more pronounced in the partial rates and their ratio. Furthermore, this ratio turns out to be sensitive to the choice of strong coupling constants as well. This finding indicates the need for improved YN potentials with better determined strong couplings at the hyperon-nucleon-meson vertices. In contrast to the previous observables we found the proton asymmetry to be very sensitive to the ρ -exchange while the influence of the kaon is more moderate. This polarization observable is therefore an important addition to the set of observables since its sensitivities are different from the total and partial rates.

Within the one-meson exchange picture it would be desirable to use weak coupling constants obtained from more sophisticated approaches. A beginning has been made by Savage and Springer [10] however, an understanding of the weak $\Lambda N\pi$ and $\Sigma N\pi$ couplings within the framework of chiral lagrangians is still missing. Furthermore, due to the importance of the K^* -meson it would be desirable to recalculate its weak NNK^* couplings in improved models as well.

In an attempt to solve the Γ_n/Γ_p puzzle, the authors of Ref. [16] studied the $3N$ emission channel ($\Lambda NN \rightarrow NNN$), where the virtual pion emitted at the weak vertex is absorbed by a pair of nucleons which are correlated through the strong force, including final state interactions of the three nucleons on their way out of the nucleus via a Monte Carlo simulation. It was shown that the new channel influences the analysis of the ratio Γ_n/Γ_p increasing its experimental error bars and leading to a value compatible with the predictions of the OPE model. However, the same calculation shows that a comparison of the proton spectrum with the experimental one favors values of $\Gamma_n/\Gamma_p = 2-3$. It is therefore imperative, before speculating further about the deficiencies of the present models in reproducing this ratio, to carry out more precise experiments such as the measurement of

the number of protons emitted per Λ decay.

We have seen that the consideration of the exchange of mesons heavier than the pion in the NM decay of hypernuclei does not change the total and partial rates in a dramatic way. A different approach to the problem can be found in Ref.[17], where the authors compare the Direct Quark (DQ) potential with a conventional OPE one, and calculate the NM decay rates of light hypernuclei. In order to fix the relative phase between both contributions, the weak $\Lambda N\pi$ coupling is related to a baryon matrix element of the weak hamiltonian for quarks by using soft-pion relations. They found that the DQ contributes the most in $J = 0$ transitions, enhancing Γ_n and therefore the neutron-to-proton ratio, and that the $\Delta I = 3/2$ components are significant in the $J = 0$ transitions. On the other hand, their nuclear matter results show that a softer cut-off for the pion (≈ 800 MeV) compared to the Born-like one used in the present contribution (1.3 GeV), seems more appropriate to reproduce experimental values of Γ_p [18].

The need for improved YN interaction models has also been pointed out in Ref. [19]. Motivated by future measurements [20] of cross sections and different polarization observables [21] for the $pn \rightarrow p\Lambda$ reaction near threshold, Ref. [19] gives a theoretical prediction using the same model as presented here, and taking advantage of the lack of nuclear structure ingredients. This study has shown that this reaction is not only sensitive to the weak ingredients of the model, but also to the strong YN interaction. The cross sections have been found to be of the order of $10^{-12}mb$, a good challenge for the improved experimental devices. The experiment should shed some light onto the understanding of the weak $\Delta S = 1$ hadronic interaction.

The hypernuclear weak decay studies are being extended to double- Λ hypernuclei[22]. Very few events involving these exotic objects — whose very existence would place stringent constraints on the existence of the elusive H-dibaryon — have been reported. Studying the weak decay of these objects would open the door to a number of new exotic Λ -induced decays: $\Lambda\Lambda \rightarrow \Lambda N$ and $\Lambda\Lambda \rightarrow \Sigma N$. Both of these decays would involve hyperons in the final state and should be distinguishable from the ordinary $\Lambda N \rightarrow NN$ mode. Especially the $\Lambda\Lambda \rightarrow \Lambda N$ channel would be intriguing since the dominant pion exchange is forbidden, thus this reaction would have to occur mostly through kaon exchange. One would therefore gain access to the weak $\Lambda\Lambda K$ vertex.

The promising hypernuclear program at KEK, after an improved measurement of the ${}^5_\Lambda\text{He}$ decay, the continuing program at BNL, which recently proved the existence of the ${}^4_\Lambda\text{He}$ hypernucleus, and the hypernuclear physics program (FINUDA) at DAΦNE, represent excellent opportunities to obtain new valuable information that will shed light onto the still unresolved problems of the weak decay of hypernuclei.

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Table 1

Nonmesonic decay observables of ${}^{12}_{\Lambda}\text{C}$. The values in parentheses have been calculated using the Jülich-B coupling constants at the strong vertex.

| | $\Gamma^{nm}/\Gamma_{\Lambda}$ | Γ_n/Γ_p | a_{Λ} |
|---------------------------|--------------------------------|---------------------|---------------|
| π | 0.89 (0.89) | 0.10 (0.10) | -0.24 (-0.24) |
| $+\rho$ | 0.86 (0.83) | 0.10 (0.10) | -0.10 (-0.05) |
| $+K$ | 0.50 (0.51) | 0.03 (0.03) | -0.14 (-0.07) |
| $+K^*$ | 0.76 (0.90) | 0.05 (0.07) | -0.18 (-0.20) |
| $+\eta$ | 0.68 (0.90) | 0.06 (0.07) | -0.20 (-0.20) |
| $+\omega$ | 0.75 (1.02) | 0.07 (0.11) | -0.32 (-0.37) |
| weak | | | |
| K -couplings | 0.84 (1.10) | 0.08 (0.11) | -0.30 (-0.35) |
| from χPT [10] | | | |

Table 2

Weak decay observables for various hypernuclei. The values in parentheses have been calculated using the NNK weak coupling constants obtained when including one-loop corrections to the leading order in χPT [10].

| | ${}^5_{\Lambda}\text{He}$ | ${}^{11}_{\Lambda}\text{B}$ | ${}^{12}_{\Lambda}\text{C}$ |
|-----------------------------|---------------------------|--------------------------------------|--------------------------------------|
| Γ/Γ_{Λ} | 0.41 (0.47) | 0.61 (0.69) | 0.75 (0.84) |
| EXP: | 0.41 ± 0.14 [23] | $0.95 \pm 0.13 \pm 0.04$ [24] | 1.14 ± 0.2 [23] |
| | | | $0.89 \pm 0.15 \pm 0.03$ [24] |
| Γ_n/Γ_p | 0.07 (0.09) | 0.08 (0.10) | 0.07 (0.08) |
| EXP: | 0.93 ± 0.55 [23] | $1.04^{+0.59}_{-0.48}$ [23] | $1.33^{1.12}_{-0.81}$ [23] |
| | | $2.16 \pm 0.58^{+0.45}_{-0.95}$ [24] | $1.87 \pm 0.59^{+0.32}_{-1.00}$ [24] |
| | | 0.70 ± 0.3 [25] | 0.70 ± 0.3 [25] |
| | | 0.52 ± 0.16 [25] | 0.52 ± 0.16 [25] |
| $\Gamma_p/\Gamma_{\Lambda}$ | 0.39 (0.43) | 0.56 (0.62) | 0.71 (0.78) |
| EXP: | 0.21 ± 0.07 [23] | $0.30^{+0.15}_{-0.11}$ [24] | $0.31^{+0.18}_{-0.11}$ [24] |
| a_{Λ} | -0.27 (-0.27) | -0.39 (-0.38) | -0.32 (-0.30) |
| EXP: | 0.22 ± 0.20 [15] | | |
| $\mathcal{A}(0^\circ)$ | | -0.12 (-0.12) | -0.03 (-0.03) |
| EXP: | | -0.20 ± 0.10 [13] | -0.01 ± 0.10 [13] |